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HUMAN VISUAL ACUITY MEASURED WITH COLORED STIMULI

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Carl Richard Cavonius

September 1965

U.S. Army Medical Research and Development Command
Office of the Surgeon General
Washington D.C. 20315

Contract No. DA-49-193-MD-2666

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Human Sciences Research Inc.
Westgate Research Park
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SUMMARY

Visual acuity was measured with acuity targets in which target and background were matched in brightness but differed in wavelength, in order to determine whether brightness contrast is a necessary condition for the discrimination of fine detail. The acuity target was a grating in which alternate bars were illuminated by two equally bright monochromatic sources. The width of the bars was varied optically to establish the observer's acuity threshold.

When adjacent bars were illuminated with nearly the same wavelength acuity was predictably poor. Acuity improved rapidly when wavelength separation was increased. Sufficient wavelength separation resulted in acuity scores which are comparable with those obtained with similar black-white targets. When maximum acuity was reached by means of wavelength separation, no further improvement could be made by introducing a brightness mismatch.

The wavelength separation which is required to obtain good acuity varies with the part of the spectrum which is tested. It is smallest at short wavelengths and increases greatly in the red. It does not appear to be related to the wavelength discrimination function measured with large fields.

It is concluded that hue contrast alone can be a sufficient condition for good visual acuity. However, the hue of small targets cannot be identified even though the presence of the targets is obvious.

FOREWORD

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HUMAN VISUAL ACUITY MEASURED WITH COLORED STIMULI

I. Introduction

Definition of Visual Acuity

Visual acuity can be defined as the ability to perceive fine detail. As is the case with many concepts related to perception, it is impossible to formulate a rigorous definition since such a definition would lack generality. This is true because the meaning of visual acuity depends upon the situation in which it is being measured. A review of the literature dealing with visual acuity and a discussion of the ways in which it may be measured would be redundant since two recent articles (Riggs, 1965; Westheimer, 1965) discuss these topics in detail.

Although the exact meaning of visual acuity may be moot, the units used to describe acuity are fairly well standardized. In research, visual acuity is frequently expressed as the reciprocal of the visual angle (measured in minutes of arc) which is subtended by the test object when it can just be resolved by the observer. Thus, if an observer can just discriminate an object which subtends 1 minute of arc at his eye he is said to have a visual acuity of 1.00, under these viewing conditions. (The dimension min^{-1} is usually omitted.) This rather arbitrary unit has several advantages: the resulting numerical values are convenient to work with and increase as visual acuity improves, instead of being an inverted scale like target distance, width, or angular subtense; and they may be easily converted into the clinician's Snellen notation by re-writing them as a fraction in which the numerator is 20. (That is, visual acuity of 1.00 is considered to be equivalent to a Snellen score of 20/20. It should be remembered, however, that this conversion may be meaningless if visual acuity is measured with test materials which are unlike the Snellen Chart.)

No normal observer has a single fixed visual acuity under all test conditions. Rather, his acuity varies with the test situation. Higher scores are generally obtained when acuity is measured with simple stimuli (dots and fine lines) and lower scores are obtained with complex stimuli (grating, Landolt C, or letters). An observer who has a visual acuity of 1.00 when measured with Snellen test type may reach a score of 100.00 when tested with fine lines.

It will be noted that measures of visual acuity do not specify the distance from the observer to the acuity target. In some test situations it may be necessary to state this distance, since acuity appears to change

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at short viewing distances, when accommodation becomes critical (Giese, 1946). Most experimental tests of acuity use a relatively long viewing distance at which acuity changes only slightly with distance.

Historically, most studies of visual acuity have been performed with achromatic test materials, in which there is a brightness difference between the areas which are to be discriminated. Hartridge (1922) showed that most acuity data could be explained by assuming that adjacent receptors can discriminate small differences in light intensity. Since then visual acuity has often been considered as a special case of differential luminance sensitivity (e.g., Hendley, 1948). Hartridge (1922) calculated that an intensity difference of 10% between adjacent receptors is necessary if the observer is to perceive fine detail. Hecht and Mintz (1939) showed that dark lines on an illuminated background could be discriminated when the brightness difference between adjacent rows of receptors is as small as 1%. This does not refute Hartridge's theory, however, since a 1% brightness difference is still greater than the differential luminance threshold measured with large fields. Referring to this, Hartridge (1947) states: "It is important that this point should be fully appreciated, for as these revised acuities are reported as the result of further research, the idea seems to be prevalent that they refute the author's theory. Such is not the case, however; the value of the least perceptible intensity difference may need revision from time to time, but the theory itself will remain unchallenged until some one proves that resolution is in fact taking place when there are no differences of light intensity to be perceived by the fovea."

While it is not fair to adopt too literal an interpretation of Hartridge's position, it is quoted here since in the experiment to be described visual acuity was measured in a situation in which every effort was made to eliminate brightness gradients as stimuli.

Effect of Color on Visual Acuity

Only a small part of the vast literature on human visual acuity is concerned with the effects of stimulus wavelength. Studies in which wavelength was a variable may be divided into two categories:

1. Studies in which either the target or (more frequently) the background was colored, the remaining portion being achromatic (e. g., a black Landolt C on a colored background), or in which both target and background were the same hue, but differed in brightness.

2. Studies in which both target and background were colored, but differed in hue and/or saturation.

Each of these categories may be further divided according to whether or not the colors used were of equal brightness, and whether or not a correction was made for the chromatic aberration of the observer's eye.

Experiments of Type 1 are summarized in Table I. In general it can be concluded that wavelength has relatively little effect on visual acuity provided that (1) all illuminants are matched in brightness and (2) the axial chromatic aberration of the human eye is corrected. Differences in the results of these studies can probably be accounted for by the above two factors. The effect of chromatic aberration is shown in Baker's study. Of the several colors tested, blue illumination resulted in the poorest acuity when the unaided eye was tested, and the best acuity when chromatic aberration was corrected. Chromatic aberration probably accounts for Ferree and Rand's conclusion that colors near the middle of the visible spectrum give the best acuity, since no correction for aberration was used in this study. Roaf found extremely poor acuity when his stimuli were illuminated with blue light. This is probably due to his method for matching brightness (by equating all colors at the scotopic threshold and then raising all intensities by an equal amount).

Still fewer studies have been done with colored targets and backgrounds (Type 2 above). The lack of research in this area is surprising in view of its possible implications to theories of color vision. An evaluation of the Young-Helmholtz theory led to an early study of this type (Brücke, 1879). In order to evaluate the relative effectiveness of brightness contrast and hue contrast in the discrimination of fine detail, Brücke fastened small squares of colored paper to an equally bright background of another color and measured the viewing distance at which the orientation of the squares could be correctly identified. He compared this distance with the distance at which the orientation of similar black squares on a white background could be correctly identified, and found that a black-white pattern could always be identified at a greater distance than a colored pattern of the same size. He therefore concluded that brightness difference is more important than hue difference in the perception of detail.

Similar results were obtained by Exner (1898), von Lempicka (1919), Liebmann (1927), and Hartridge (1947). These experimenters used striped targets made of colored papers or colored ink. Exner wished to determine whether better acuity could be obtained by using

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TABLE 1 STUDIES OF VISUAL ACUITY AS A FUNCTION OF ILLUMINANT WAVELENGTH

Investigators	Stimulus Material	Brightness Match	Artificial Pupil	Correction for Chromatic Aberration	Psychophysical Method	Stimulus Wavelength or Hue	Saturation	Results
Arnault & Flamant (1950)	Grating (black on color)	Heterochromatic match	Yes Varied from .24 to 4.0mm	No	Unknown	642 546 405 white	Very good (monochromator plus filter)	Small pupil: green, white, red. Large pupil: no difference between colors.
Baker (1949)	Black vernier target on color	Heterochromatic match	2.8mm	Yes (Part of the time)	Adjustment	690 575 490 white	Fair (Wratten filter)	Without correction: red, yellow, white, blue. With correction: blue, red, yellow, white.
Bishop (1961)	Two small black rectangles on color, or colored rectangles on black	Calibrated photocell	1, 2, 3, 4, and 5mm	No	Observer moves targets together or apart until gap between rectangles just visible.	632 588 538 500 462	Good (Corning filters)	With large pupil, middle of spectrum generally better. With small pupil, no difference.
Boltunow (1908)	Landolt C (black on color)	Equated by flicker photometry	Natural	No	Observer approaches stimulus	red green white	Probably poor (colored glass)	White best, green intermediate, red worst.
Ferree & Rand (1931)	Landolt C (black on color)	Heterochromatic match	Natural	No	Single stimuli	666 624 578 563 522 501 488	Good (spectroscope)	Center of spectrum gives best acuity - both ends are depressed.
Hartridge (1947)	Letters, Landolt C (black on color)	Heterochromatic match	2mm	Yes	Single stimuli	red (>600) green (c. 550) blue (<500) white (sunlight)	Poor (broad filters)	White and green best, slightly better than red and blue.
Liebmann (1927)	Grating (adjacent stripes of same color, slightly different brightness)	Heterochromatic match	Natural	No	Observer approaches stimuli	red orange green blue gray	Poor (colored papers)	No difference between colored gratings and achromatic gratings with same brightness difference.
Rice (1912)	Black letters on color	Equated by flicker photometry	Natural	No	Observer approaches stimuli	red white green blue	Poor (colored light bulbs)	Red best, blue and green both slightly worse.
Roaf (1930)	Black letters on color	Equated at absolute threshold only	Part of the time	Yes	Increase intensity until stimuli visible	red green (c. 540) blue (<480) white	Poor (broad filters)	White best, red and green equal, blue much worse even at maximum intensity.
Shlaer, Smith & Chase (1942)	Grating and Landolt C (black on color)	None; brightness for all colors high enough to reach maximum acuity	Several sizes	Yes	Adjustment (increasing visual angle only)	670 625 605 575 white 535 490 450	Fair (Wratten filters)	Grating target: green best, then blue, white, yellow, violet, red (limited by artificial pupil). Landolt C: all colors gave same acuity.

complementary colors for the target and background. He concluded that brightness contrast has more effect on acuity than does color contrast, and that complementary colors do not yield better acuity than any other pairs of colors. Von Lempicka (1919) tested acuity with black-white, yellow-blue, and red-green gratings and found that the acuity scores measured with these combinations followed the same rank order as the brightness contrasts of the stimuli. Curiously, however, a grating made of equal brightness red-green bars gave significantly better acuity than a grating of red-gray or green-gray bars.

Liebmann (1927) varied the brightness contrast between adjacent bars of a neutral gray grating until her observers could see individual bars at the same viewing distance as the distance at which they could identify the colors of the bars in a grating made of alternating red and green bars. She found that only a very small brightness difference between bars in the achromatic grating was needed in order to see it at the same distance as the red-green gratings. Similarly, black-white gratings could be discriminated about twice as far away as gratings made of any two colors from the series red, green, yellow and blue.

Liebmann's instructions to her observers should be noted, since they differ from the usual acuity task. Her observers were told to approach the target until they could clearly perceive the color of individual bars. We have found that a grating target must subtend a significantly larger visual angle if individual colors are to be discriminated than the visual angle required to merely detect the presence of the grating.

Several other studies are sometimes cited as relevant to this area. Koffka and Harrower (1931) investigated the influence of colored stimuli and backgrounds on the perception of form. It is doubtful whether their results can be directly related to visual acuity, since their stimuli were complex, and since perception of form almost certainly involves more than just visual acuity.

Sumner (1932) and Preston, Schwankel and Tinker (1932) studied the practical problem of increasing the legibility of text printed with colored ink on colored stock. No attempt was made to equate the brightness of stimulus and background. While their results are complex, they show that brightness contrast tends to enhance legibility.

Brindley (1954) measured acuity by using grating stimuli in which bars of one color were optically superimposed on backgrounds of another color. He used backgrounds of several colors,

which were heterochromatically matched for brightness. Brindley showed that visual acuity increases with the intensity of the super-imposed bars, and that the shape of this acuity-intensity function is different for violet (454 nm) bars on a red (680 nm) or green (548 nm) background than it is for red bars on a green background or green bars on a red background. However, the luminances of the three colors used for the bars does not appear to have been equated. Hence it does not necessarily follow that grating acuity for blue targets on a red or green background is poorer than for red targets on a green background or green on a red background, as concluded by Westheimer (1965) on the basis of Brindley's results. Further, this study does not directly relate to chromatic acuity since the luminance of the target bars was added to that of the background, so that the observer saw bars of one color (background) alternating with bars of target added to background. Thus, a luminance difference existed between adjacent bars.

Hartinger and Schubert (1940) tested acuity with Landolt C targets made of colored papers applied to colored backgrounds. They were primarily interested in evaluating the effect of colored glasses on acuity, and not in the problem of chromatic acuity as such. Their data show that (regardless of the viewing glasses used) acuity tends to improve with increasing luminance contrast.

It should be noted that with a single exception (Brindley) all of the Type 2 studies cited above used stimuli made of colored papers. The saturation which can be obtained with pigments is limited. This may explain the finding that hue contrast is relatively ineffective as a stimulus for visual acuity since, in the study by Crook et al (1959) described below, high saturation was found to be necessary for good acuity.

Two modern studies bear directly on the problem of chromatic acuity. One is a wartime NDRC project performed by the Eastman Kodak Company (1944) in which Landolt C's cut from Munsell papers were viewed against equally luminous backgrounds of another hue, under conditions of moderate glare. No correction was made for chromatic aberration. Since the stimuli were colored paper, the range of stimulus saturation was limited. Despite this, acuity thresholds of substantially less than one minute of arc were found with some combinations of stimulus and background. Increasing hue or saturation difference between the Landolt C and its background improved acuity. Increasing adaptation level improved acuity based on chromatic contrast in the same way as it improves acuity based on luminance contrast. Since, for practical applications, it was important to be able to predict the combined effect on acuity of chromatic contrast and luminance contrast, chromatic acuity scores in the Kodak

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study are expressed in terms of the brightness contrast necessary to obtain the same acuity. An expression was derived from the experimental data which roughly predicts acuity when the stimulus and surround differ both in chromatic contrast and brightness contrast.

A recent study from the Tufts Institute for Psychological Research (Crook et al., 1959) used more highly saturated stimuli generated with Corning glass filters. The stimuli consisted of two small rectangles which could be varied in wavelength and intensity. These were displayed on a larger background which was similarly adjustable. The observer was required to move the rectangles toward or away from each other until the gap between them was just perceptible. This stimulus, which was intended to simulate targets on a radar screen, has elements similar to both fine line and Landolt C targets, but cannot be directly compared with either, or to any other conventional stimuli. However, the same researchers also measured acuity by using similar achromatic targets, so that acuity based on chromatic contrast could be compared with acuity based on luminance contrast. In general, the best acuity thresholds were about the same for either chromatic contrast or luminance contrast, and both were below 0.5 minutes of arc. Curiously, the addition of luminance contrast to brightness contrast did not always improve acuity, and sometimes actually degraded it. Best acuity was found when targets and background were of maximum purity. Blue and violet targets gave relatively poor acuity, probably because of chromatic aberration. Since many other target characteristics (shape, size, luminosity, etc.) were investigated in this study, only a limited number of color combinations could be used. A follow-up study by Bishop (1961) confirmed the fact that visual acuity could be quite good with only chromatic contrast. Bishop believes that in this stimulus situation the observers attend primarily to the targets and not to the background, since changing the background illuminant has less influence on the results than changing the target illuminant.

Present Study

This experiment was designed to answer the following question: Is a brightness gradient necessary for good visual acuity?

The related experimental problem is: How does visual acuity vary as a function of target and background wavelengths when monochromatic targets are presented on monochromatic backgrounds of equal brightness?

During the course of the experiment, visual acuity was also tested with monochromatic targets on a black background, since

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previous experiments which used similar stimuli gave somewhat conflicting results.

A definitive study of chromatic visual acuity should meet several requirements:

1. A conventional acuity target should be used, so that results may be compared with published data on achromatic acuity.

2. Maximum saturation stimuli should be available.

3. If the purely retinal aspects of acuity are to be studied, provision must be made to correct the chromatic aberration of the eye.

4. Stimulus brightness must be matched on the basis of the individual observer's spectral sensitivity function.

Although it was not expected at the beginning of the study, the last requirement proved to be extremely important, since we have found that very slight changes (e.g., 0.05 log units) in the relative intensities of stimulus and background can significantly change the measured acuity under some conditions. For this reason luminance settings made with a photocell, or luminance settings based on the Commission International de l'Eclairage (C.I.E.) standard observer or the Munsell system, are unsatisfactory at times.

Grating targets consisting of alternate bars of equal width were used in this study because so much data has been obtained by other investigators using similar gratings, and since the light distribution at the retina can be computed for a grating but is virtually unsolvable for more complex patterns, such as letters. Current interest in the application of Fourier theory to optics has renewed interest in the use of gratings. Wertheimer (1965) suggests that gratings are the most satisfactory targets from a theoretical point of view.

The terms "target" and "background" have no clear meaning in the case of a grating since either set of bars can equally well be thought of as target or background. The terms have been retained in this discussion because of their common use and since no better terms suggest themselves.

In order to obtain highly saturated stimuli, and to enable the selection of any wavelength within the visual spectrum, high intensity grating monochromators were used to illuminate the targets and backgrounds. These instruments have the advantage of constant dispersion and hence a constant bandpass across the spectrum. A nominal bandpass of 10 nm was used throughout the study.

Axial chromatic aberration of the observer was largely eliminated by use of an artificial pupil and an overcorrected achromat (Hartridge, 1918). These elements could be removed in order to test acuity in a more nearly normal viewing situation.

II. Method

Apparatus

The stimulus system produces a display which is seen by the observer as a 1 degree circular field within which the grating targets are presented. The bars of the grating are continuously adjustable in width, and alternating pairs of bars (i.e., "target" and "background") can be independently varied in hue and brightness.

The optical system is shown in Figure 1. It consists of two similar paths, each of which includes a Bausch and Lomb high-intensity grating monochromator (blazed for the visible spectrum), Bausch and Lomb evaporated metal neutral density filters, and Kodak neutral density wedges. A flicker vane (C) can be introduced to interrupt the two paths alternately, in order to perform flicker photometry. The two paths are merged at the acuity target (G), which is a first surface mirror from which portions of the reflecting surface have been removed, resulting in a grating with alternating bars of mirror and clear glass. (The technique for making these targets is described in Appendix A.) Light from one monochromator passes through the clear areas and is blocked by the silvered areas, which in turn reflect light from the other monochromator. Thus, the grating appears to the observer as alternating bars of two colors. Since the mirror surface is microscopically thin, no appreciable separation or boundary exists between adjacent bars. The mirrored surface of the target is oriented toward the observer so that refraction within the glass has no effect. The grating is seen by the observer through a variable focal length ("zoom") lens and eyepiece. A 16mm Angenieux zoom system which is adjustable in focal length from 17.5mm to 70mm was used. With the 150 line pair per inch grating which was used during most of the study, varying the focal length of this lens permits a range of adjustment of 0.55 to 2.0 minutes of arc in the width of each grating bar as seen by the observer. This corresponds to visual acuities of 1.8 to 0.5. Visual angles outside this range can be obtained by changing the grating.

Chromatic aberration is corrected by a 1.5mm artificial pupil and an overcorrected achromat designed by Hartridge (1918). This consists of a negative flint glass lens of 15mm focal length neutralized in magnification by a convex crown glass lens of the same focal length. All other lenses in the system are achromats.

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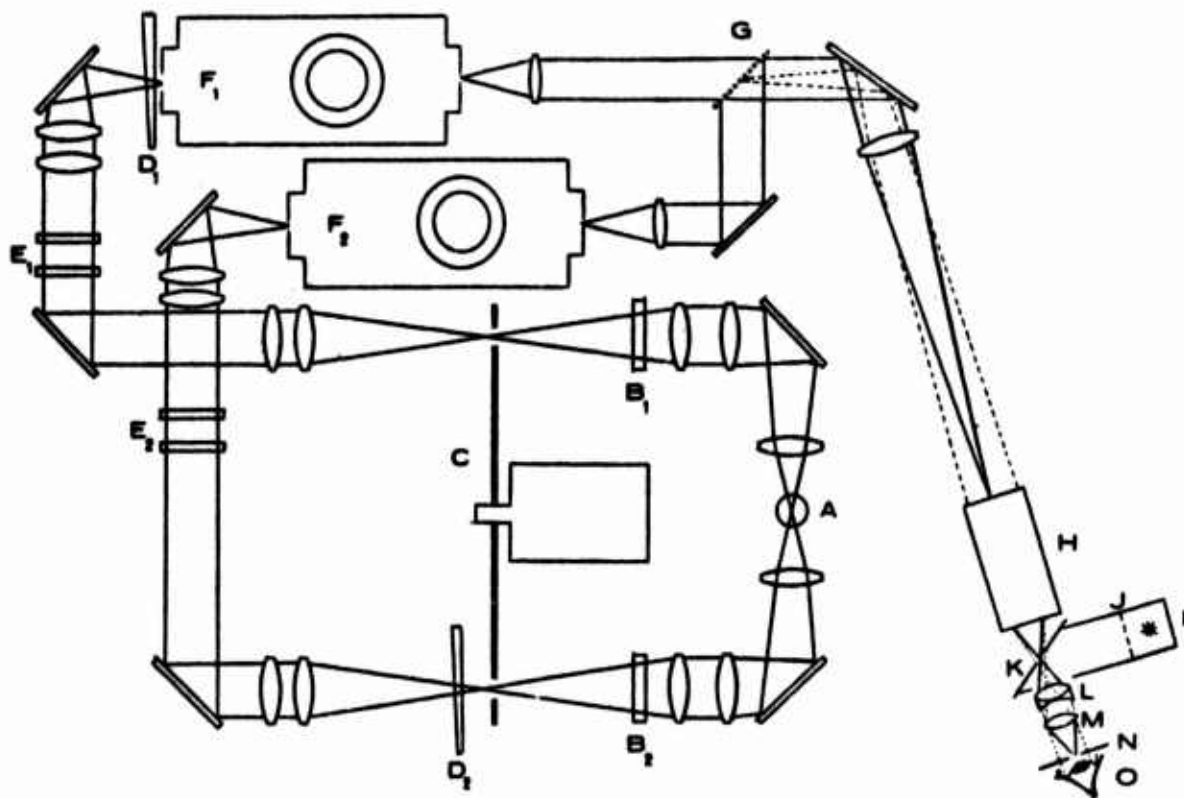
Fig. 1. Optical System. Scale $= \frac{1}{4} : 1$. Envelope of rays from the source (A) are shown as solid lines. Dotted lines represent rays from a point on the grating target (G), drawn as if it were a source.

A. General Electric T-10 ribbon filament microscope illuminator.
B. Heat absorbing glass.
C. Removable flicker vane.
D. E.K. 20x3 cm 0-1 log neutral density wedge filters.
E. Bausch and Lomb evaporated metal neutral density filters.
F. Bausch and Lomb High Intensity grating monochromators (33-86-25-02).
G. Grating target.

H. Angenieux 17.5-70 mm variable focal length lens.
I. Surround source (6 V 32 cp headlamp).
J. Diffusing screen.
K. Surround and aperture.
L. Correction for chromatic aberration (overcorrected achromat).
M. Eyepiece.
N. Artificial pupil.
O. Observer.

The observer sees an image of the grating in a modified Maxwellian view. When the artificial pupil is removed, an image of the source is formed approximately at the observer's pupil, creating a typical Maxwellian view. However, when the artificial pupil is introduced it becomes the exit pupil of the system, since it is always smaller than either the source image or the observer's natural pupil. The stimulus is seen through an aperture in a white matte surface which forms a 30 degree neutral surround. The surround is illuminated with a 6 V 32 cp tungsten lamp operated from the same power supply as the source, and appears subjectively white.

Head position is maintained by a bite board which bears an impression of the observer's bite in dental wax, and a forehead rest.

Photometric calibration was performed by setting complementary wavelengths (490 and 610 nm) in the two beams. These had previously been matched for brightness as described in the Procedures section. The grating was made too fine to be resolved, so that the resulting mixture appeared white. This was matched in brightness with an adjustable white field viewed with the natural pupil. The luminance of the comparison field was then measured directly, with the result that the stimulus pattern was equivalent in luminance to a directly viewed field of 7 foot-Lamberts. This field would cause a retinal illumination of approximately 200 effective trolands (LeGrand, 1957, p. 104). The brightness of the surround was adjusted to appear half as bright as the stimulus field, by adding diffusing material. Lythgoe (1932) has shown that maximum acuity is reached when surround brightness is slightly less than that of the stimulus.

Relative energy calibrations of the two stimulus paths were made with an International Rectifier Co. "sun battery" photocell which had been calibrated against an Eppley thermopile by Dr. Richard Srebro of WRAIR. The photocell was placed at the position of the observer's pupil and its output was measured with a Keithley microammeter. Neutral filters were placed in the stimulus path in order to obtain the same radiant energy output at each wavelength (about 10^{11} quanta/second). The two stimulus paths were calibrated separately.

Wavelength calibration of the monochromators was done by replacing the tungsten source with an Osram Hg-Cd spectral lamp. The monochromators were set for maximum brightness at each of the principal visible lines, by observing the output slits directly. Differences between the wavelength drum settings and the correct values were noted.

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Procedure

Subjects

The data to be reported was obtained from the right eyes of two observers. Both were emmetropic and had normal color vision when tested with American Optical Pseudoisochromatic Plates. Neither had any significant astigmatism.

Brightness Matching

The stimuli were matched in brightness individually for the two observers. This was done with a grating target with wide (6 degree) bars in place of the usual acuity target. One optical path was set for maximum energy output at 430 nm. The other monochromator was set at 435 nm and its intensity adjusted by the observer until both sets of bars seemed equally bright. The first path was then set at 440 nm and its brightness matched to the second, and so on. In the reverse direction (from long to short wavelengths) the wavelengths set on the two monochromators were interchanged, so that each path was set at each 5 nm interval. Results of one series of brightness matches are shown in Figure 2. Cumulative errors were reduced by performing these matches in three steps: 430-520, 520-600, and 600-670 nm. Dividing the spectrum in this way made it possible to return to a starting wavelength with approximately 0.05 log intensity difference between initial and final settings in most cases. Subject AS found it difficult to make consistent brightness matches with short wavelength stimuli. For this subject, direct heterochromatic brightness matches were used above 525 nm. Below 525 nm, the same step-by-step method was used but brightness matches were made by flicker photometry.

Psychophysical Method

Visual acuity determinations were made with a modified method of adjustment. At the beginning of each trial the grating magnification was set at a random position which was below the observer's acuity threshold. The observer could then increase (but not decrease) the magnification until the grating could be resolved. This method was used extensively by Shlaer (cf: Shlaer, 1937). It would be unsatisfactory for absolute threshold determinations since the observer has probably passed his threshold before he recognizes the pattern. In this study, however, we are primarily interested in comparing acuity measured under different conditions, and not in measuring absolute thresholds. The method of adjustment has the advantage of being much faster than most psychophysical methods.

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Fig. 2. Spectral sensitivity function based on brightness
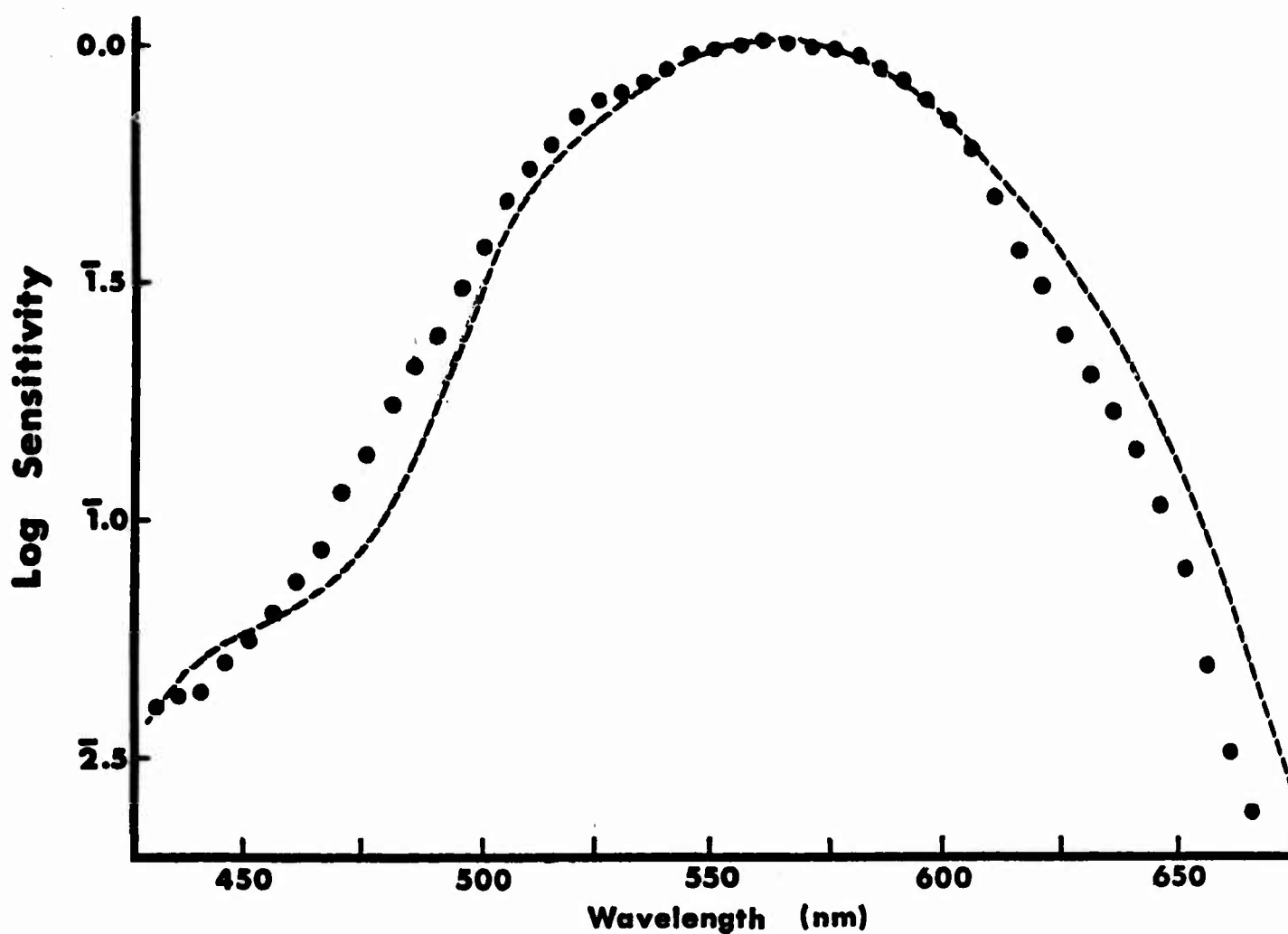matching data. Points: Sensitivity (reciprocal of
energy required to make brightness matches) for
observer CC. Line: Average spectral sensitivity
determined by Wald (1945) for a 1 degree test field
viewed foveally. Departures of data from Wald's
function may indicate inaccuracies in photocell
used for energy calibration or slight anomalies
in observer's color vision.

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This method was compared with the method of constant stimuli, which has been described as the most accurate of the psychophysical methods (Guilford, 1954). While making this comparison stimuli were used which are typical of those used in the main body of the study, and which will be described in detail later. The stimuli were monochromatic target bars presented against a monochromatic background. The background wavelength was fixed at 520 nm but the target wavelength was changed from trial to trial. Visual acuity was plotted as a function of target wavelength. In the method of adjustment the observer increased the grating size until he could resolve it, and acuity was defined as the reciprocal of the visual angle subtended by one of the grating bars at this magnification. In the constant method grating sizes were selected which covered the range from "never seen" to "always seen", and were presented in 0.5 second exposures. Five grating sizes were used within this range and the 50% seeing point was estimated by linear interpolation. Acuity was defined as the reciprocal of visual angle which would be seen 50% of the time. Results of the two methods are shown in Figure 3. In this figure all the acuity measures taken by the constant method have been lowered by 0.2 min^{-1}, which brings the two sets of data into satisfactory agreement. As predicted, the constant method yields lower thresholds (better acuity) than the method of adjustment, probably for the reason that when using the constant method the threshold is taken as the magnification at which the grating is seen 50% of the time, while for the method of adjustment the grating is seen on each trial. Except for the consistent difference of 0.2 acuity units the two methods give essentially the same results, which leads us to accept the method of adjustment as satisfactory for purposes of this study.

III. Results

Visual Acuity in Monochromatic Light

Visual acuity was measured with a grating target composed of black bars alternating with monochromatic bars of the same width. Various wavelengths within the visible spectrum were used and their brightnesses were matched by the step-by-step method described above. Acuity was tested both with and without correcting for chromatic aberration (with an artificial pupil and correcting optics). Results are shown in Figures 4 and 5. In general, wavelength seems to have relatively little effect on acuity, as was predicted on the basis of the studies summarized in the introduction. When the artificial pupil is used, diffraction appears to limit acuity above 550 nm, as shown by the agreement between measured acuity and the theoretical limit of acuity based on the Rayleigh criterion (Riggs, 1965, p. 332). When

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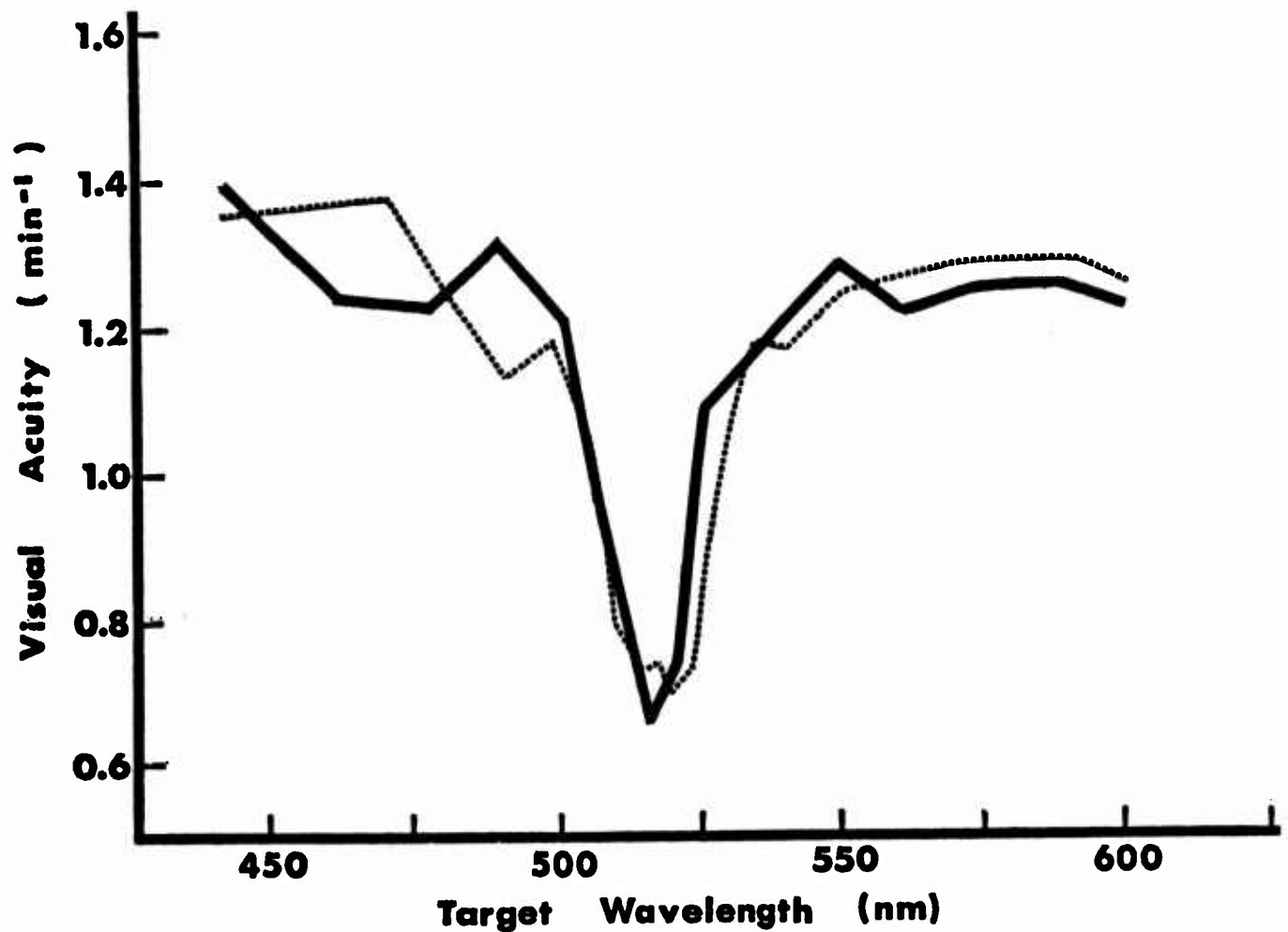
Fig. 3. Comparison of Method of Adjustment and Method of Constant Stimuli. Solid line: Constant Stimuli (0.5 sec. exposure). Dotted line: Method of Adjustment. All data for Constant Stimuli have lowered by 0.2 min^{-1}. Stimuli in both cases were colored bars (wavelength on abscissa) alternating with equally bright background bars at 520 nm.

15
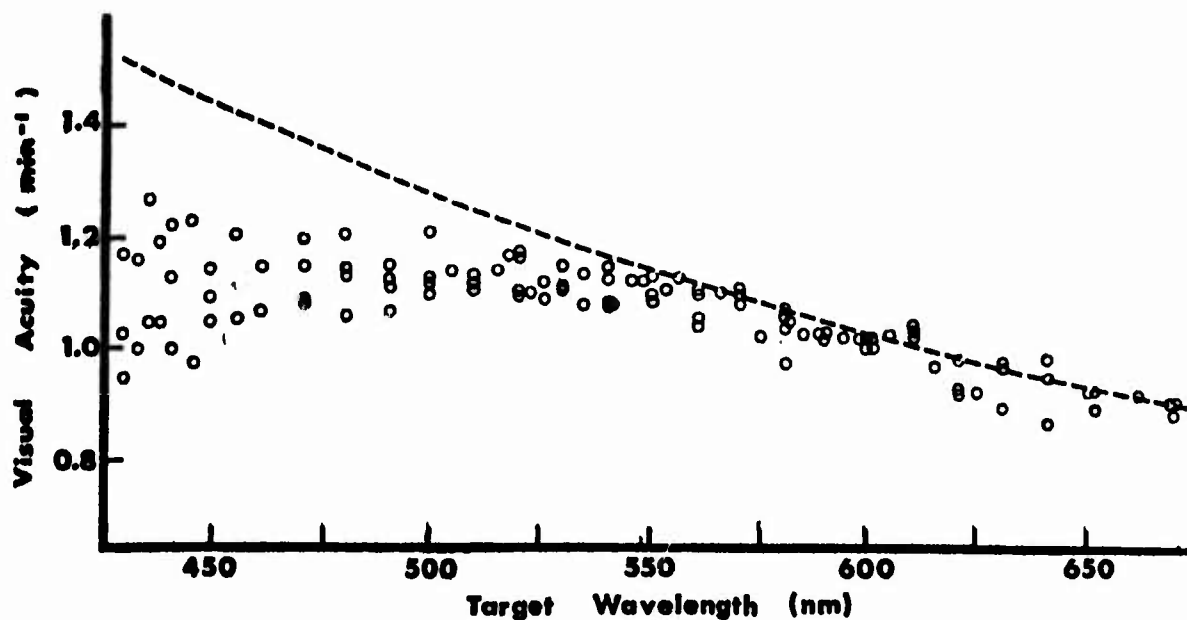
Fig. 4. Visual acuity measured in colored light. Stimulus was
a grating made up of alternating colored bars and black
bars. Points: Measured acuity. Line: Theoretical
limit of acuity based on the Rayleigh criterion. 1.5 mm
artificial pupil and correction for axial chromatic aberra-
tion were used.
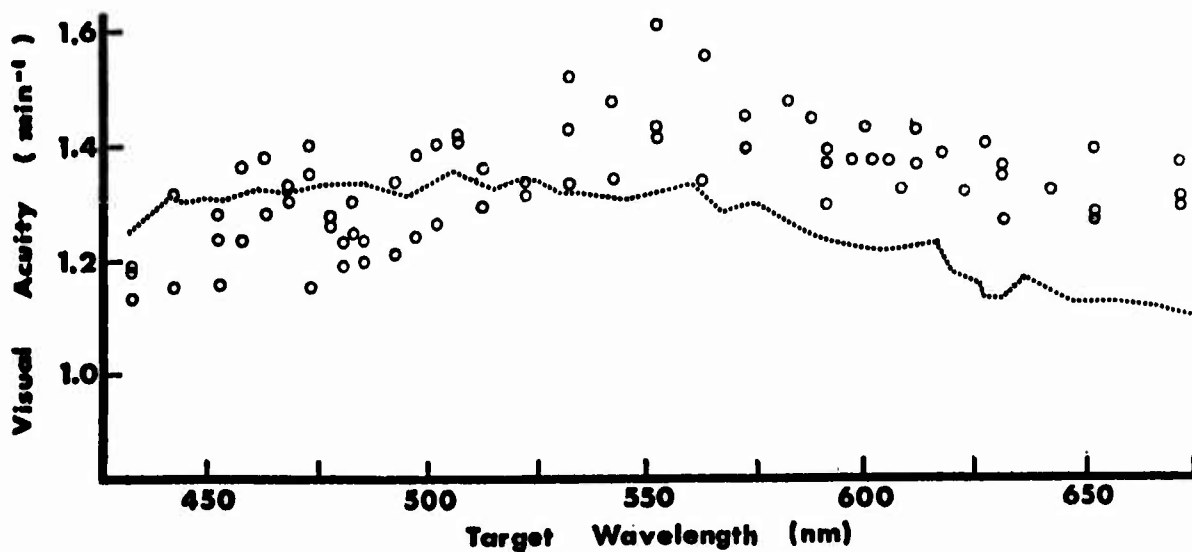
Fig. 5. Visual acuity in colored light without correction for
chromatic aberration. Points: Measured acuity.
Line: Visual acuity corrected for chromatic aberra-
tion (means of data in Fig. 4.).

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the artificial pupil is removed the acuity measured with long wavelength stimuli increases significantly, and diffraction does not appear to limit acuity.

Removal of the correction for axial chromatic aberration causes a drop in acuity at short wavelengths. This drop is not as great as might be expected on the basis of Baker's (1949) results and others. The relatively good acuity with blue stimuli is probably due to the psychophysical method used in the present study, which permitted the observer to take his time and adjust his accommodation for best acuity. The same fact may explain the greater variance shown by the data obtained without correction, since it is difficult to maintain a steady accommodation under these viewing conditions.

These observations were all made with the system focussed at 560 nm. It is probable that acuity could be improved at any given region of the spectrum by focussing in that region, except when diffraction or receptor density limits acuity.

Visual Acuity with Colored Target and Background

The major portion of this study was concerned with the measurement of acuity with stimuli in which the target and background (the alternating grating bars) were different in color but matched in brightness. This was done by leaving one path of the stimulus system at a fixed wavelength. Various wavelengths were set in the other path, and visual acuity was measured for each of these target-background combinations. The stimulus colors were matched in brightness on the basis of the step-by-step brightness functions described above. The resulting acuity values were plotted as a function of the wavelength of the variable path. Figures 6 - 9 show examples of the resulting function based on data taken with the system corrected for chromatic aberration.

As expected, acuity is best when the wavelengths of adjacent bars in the grating are far apart and becomes worse as the wavelengths are brought together. What was not expected, however, is the shape of these functions and the fact that over much of the spectrum only a rather small wavelength separation between adjacent bars is sufficient in order to reach high acuity values. This wavelength separation is not at all constant over the spectrum. As shown in these examples, only a very small difference between target and background gives good acuity when both are blue. The necessary wavelength separation increases as longer wavelengths are used.

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Fig. 6. Visual acuity measured with a target which consisted of alternating colored bars which were equated in brightness but differed in wavelength. One set of bars (background) remained at 430 nm while the other bars (target) took on the wavelengths shown on the horizontal axis.

Fig. 7. Visual acuity measured with a target which consisted of alternating colored bars which were equated in brightness but differed in wavelength. One set of bars (background) remained at 520 nm while the other bars (target) took on the wavelengths shown on the horizontal axis.

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Fig. 8. Visual acuity measured with a target which consisted of
alternating colored bars which were equated in bright-
ness but differed in wavelength. One set of bars (back-
ground) remained at 550 nm while the other bars (target)
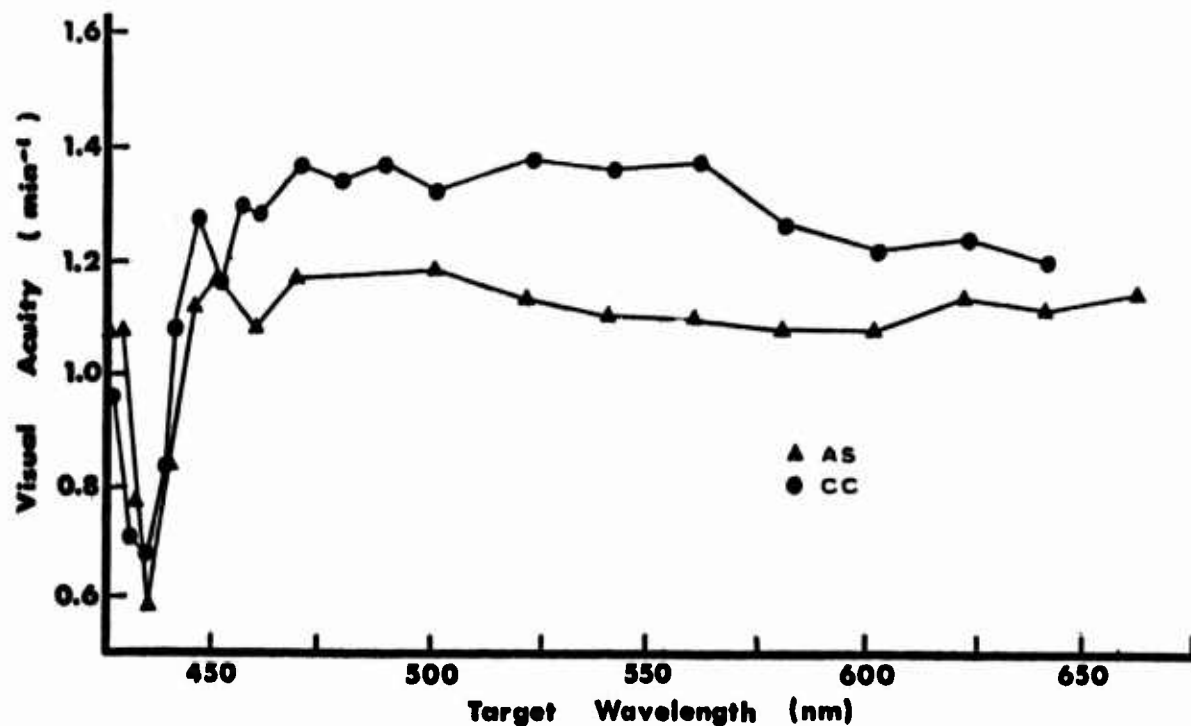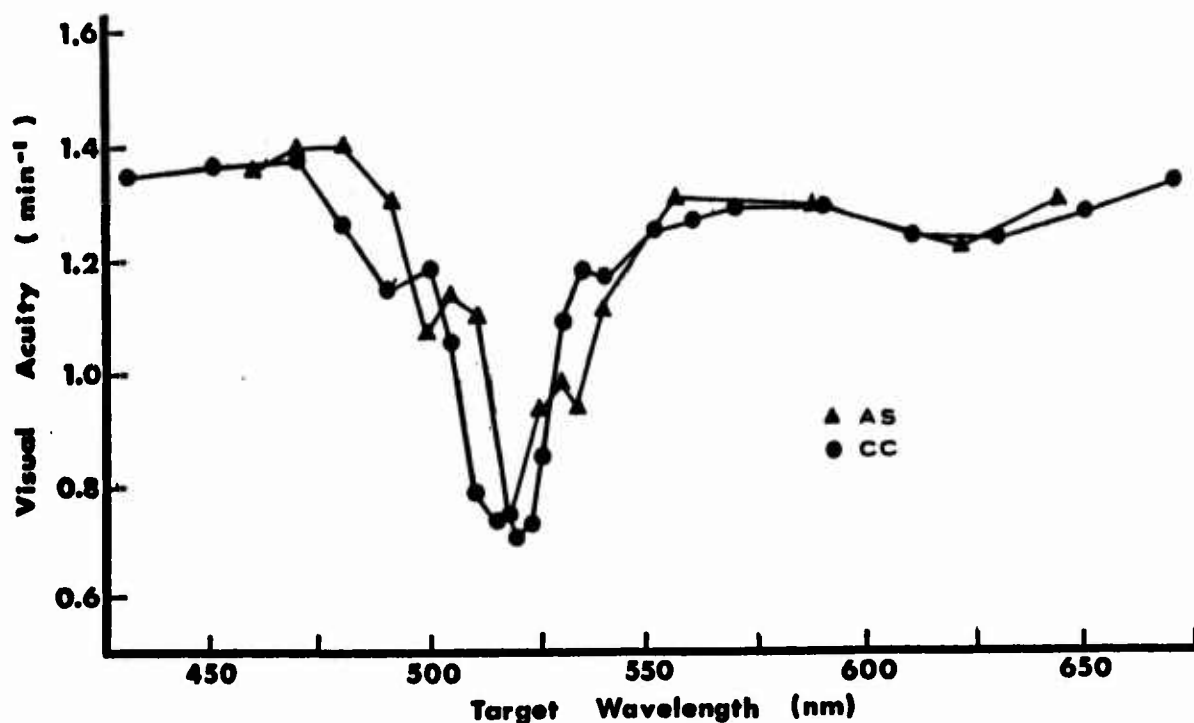took on the wavelengths shown on the horizontal axis.

Fig. 9. Visual acuity measured with a target which consisted of
alternating colored bars which were equated in bright-
ness but differed in wavelength. One set of bars (back-
ground) remained at 650 nm while the other bars (target)
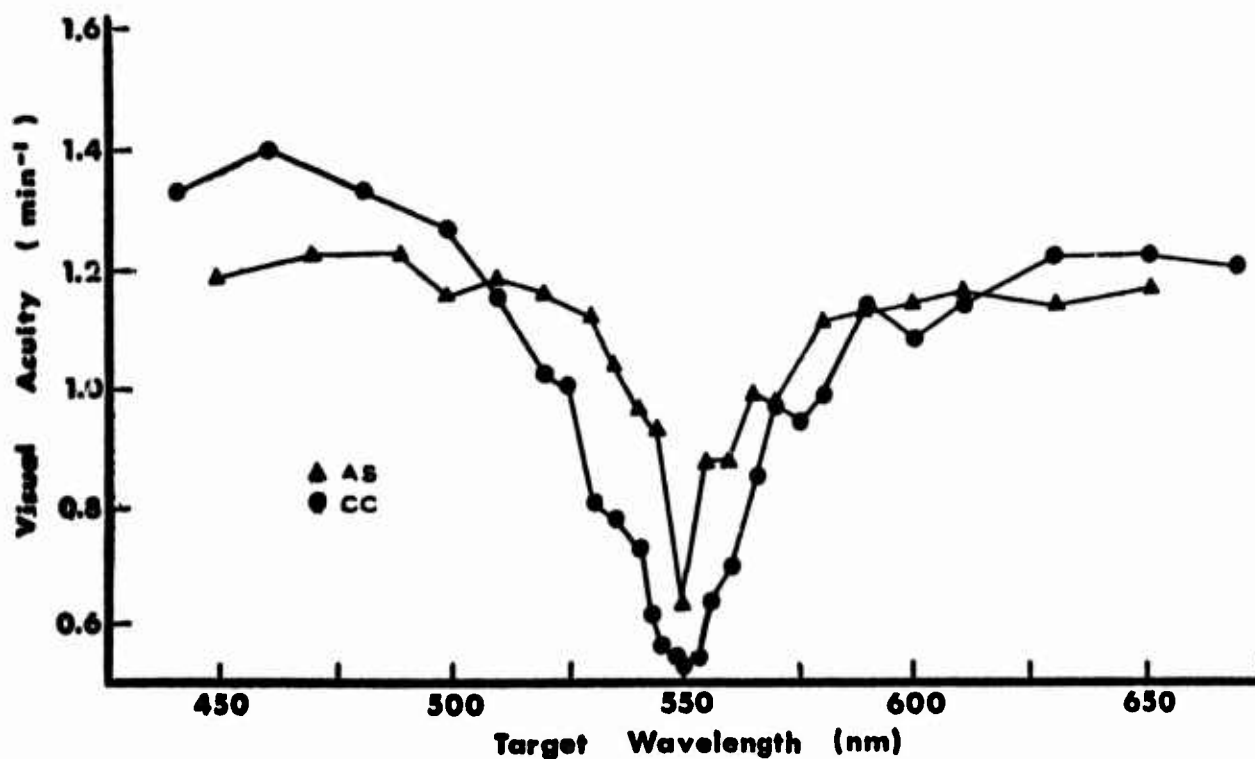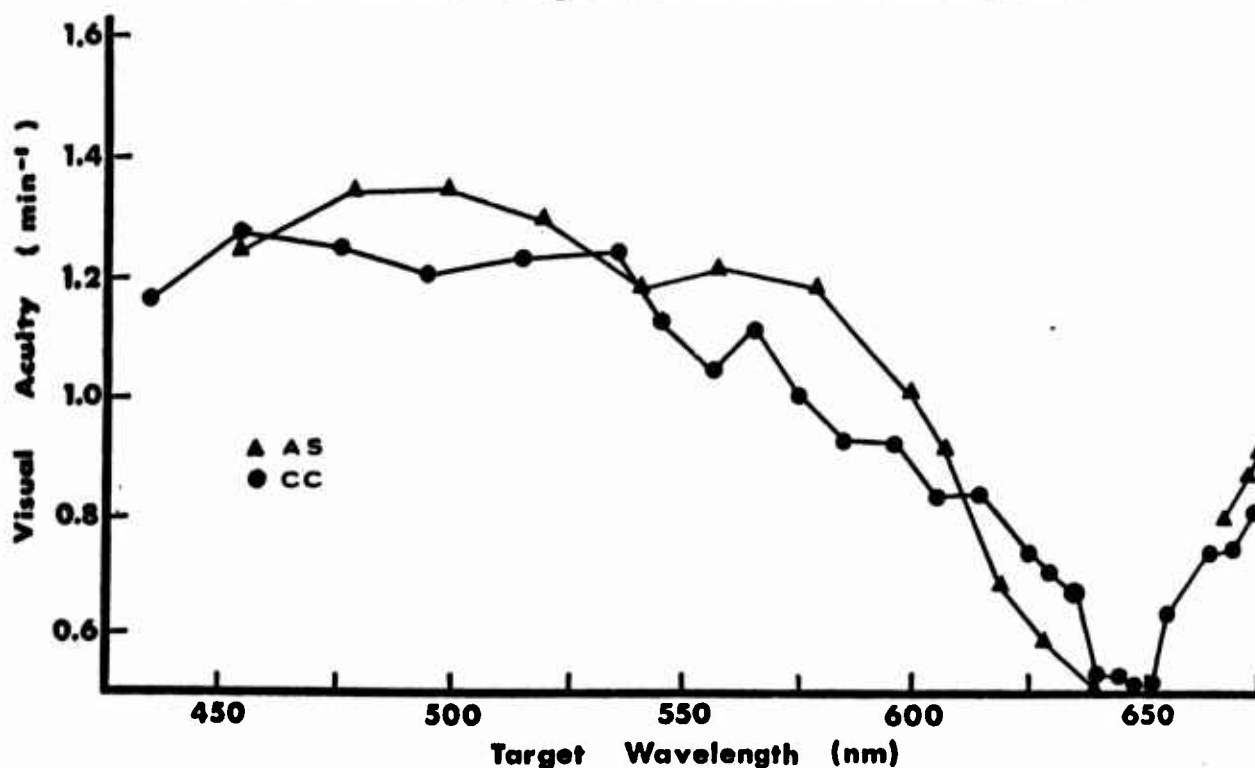took on the wavelengths shown on the horizontal axis.

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Observations Without Correction for Chromatic Aberration

In most practical applications it would not be feasible to correct for the chromatic aberration of the observer's eye. In order to examine the generality of the above results, data were also collected without the special lens and artificial pupil. Figure 10 shows two examples of these data. These results are similar to those obtained with correction except that without correction a smaller wavelength separation between target and background seems to suffice for good acuity. We have insufficient data to be certain of this, however.

Observations without correction were subjectively more difficult for the observer, probably because he must adjust his accommodation over a wide range in order to clearly focus stimuli at different wavelengths.

Measurement of the Wavelength Separation Required for Good Acuity

In order to investigate the effect on acuity of wavelength separation between target and background, more intensive measurements were made under conditions in which both wavelengths were nearly the same. Specifically, the wavelength of one set of bars was fixed, the optical system was focussed at this wavelength, and the wavelength of the alternating bars was varied (both above and below the fixed wavelength) so as to cover the range in which the observer's visual acuity varied between 0.8 and 1.2. Within this limited range, acuity increases as an approximately linear function of wavelength separation between the alternating bars. The data were plotted in the same manner as before (acuity vs. wavelength of the variable bars). A better than average example is shown in Figure 11. Similar data were obtained around fixed wavelengths at 10 nm intervals between 430 and 650 nm. From these data the interval was measured between that wavelength below the fixed wavelength which would give an acuity of 1.00, and the wavelength above which would give the same acuity. ($\Delta\lambda$ in Figure 11.) A criterion of 1.00 was selected because it is a value generally associated with good acuity in practical situations. If an operator has an acuity of 1.00 in a certain viewing condition, we know that he can function efficiently in this situation, as far as his visual system is concerned; he can read dials and fine print, and can perform other tasks requiring good visual acuity. Therefore, for practical reasons it is important to know what stimulus conditions will give a visual acuity of 1.00.
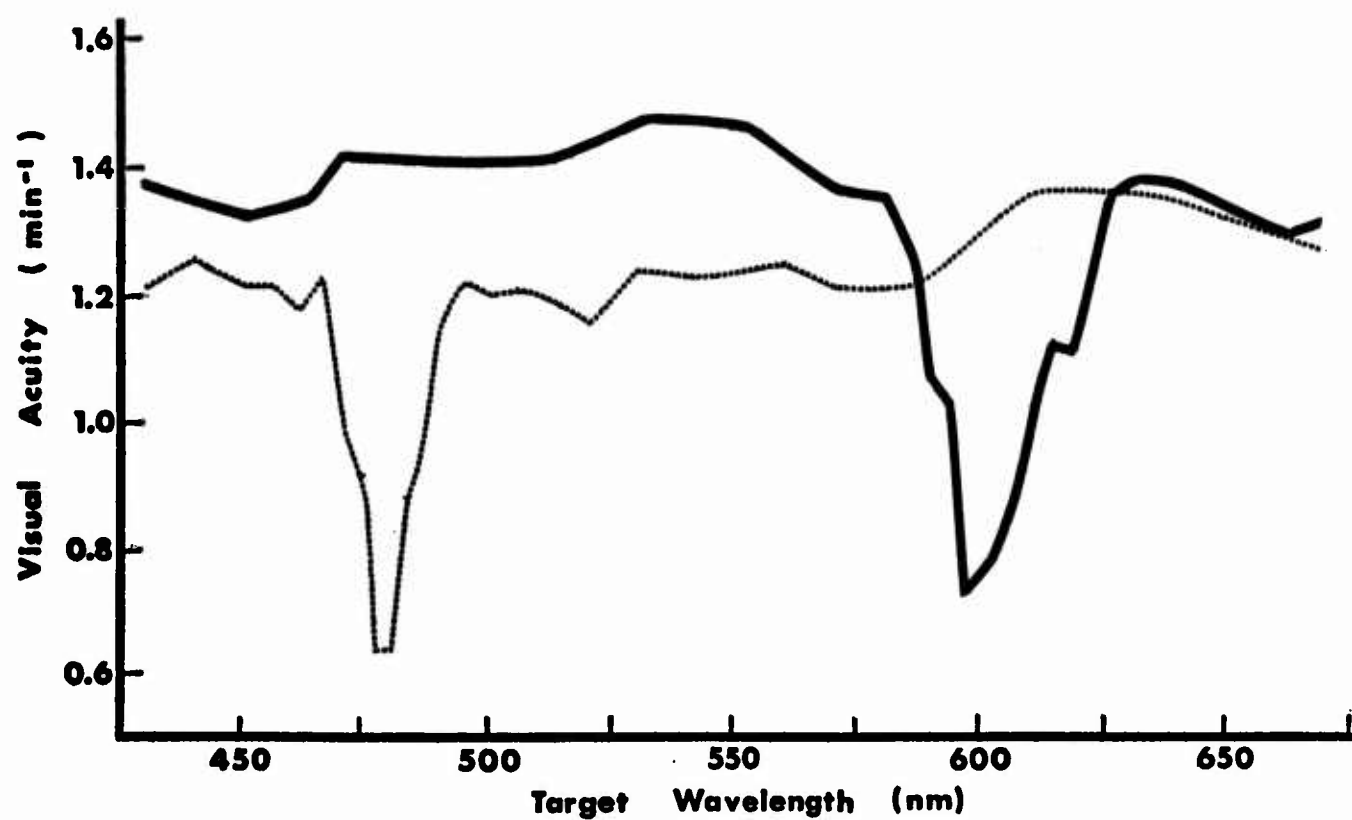
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Fig. 10.   Visual acuity measured with backgrounds at 480
(dotted line) and 600 nm (full line).   No correction
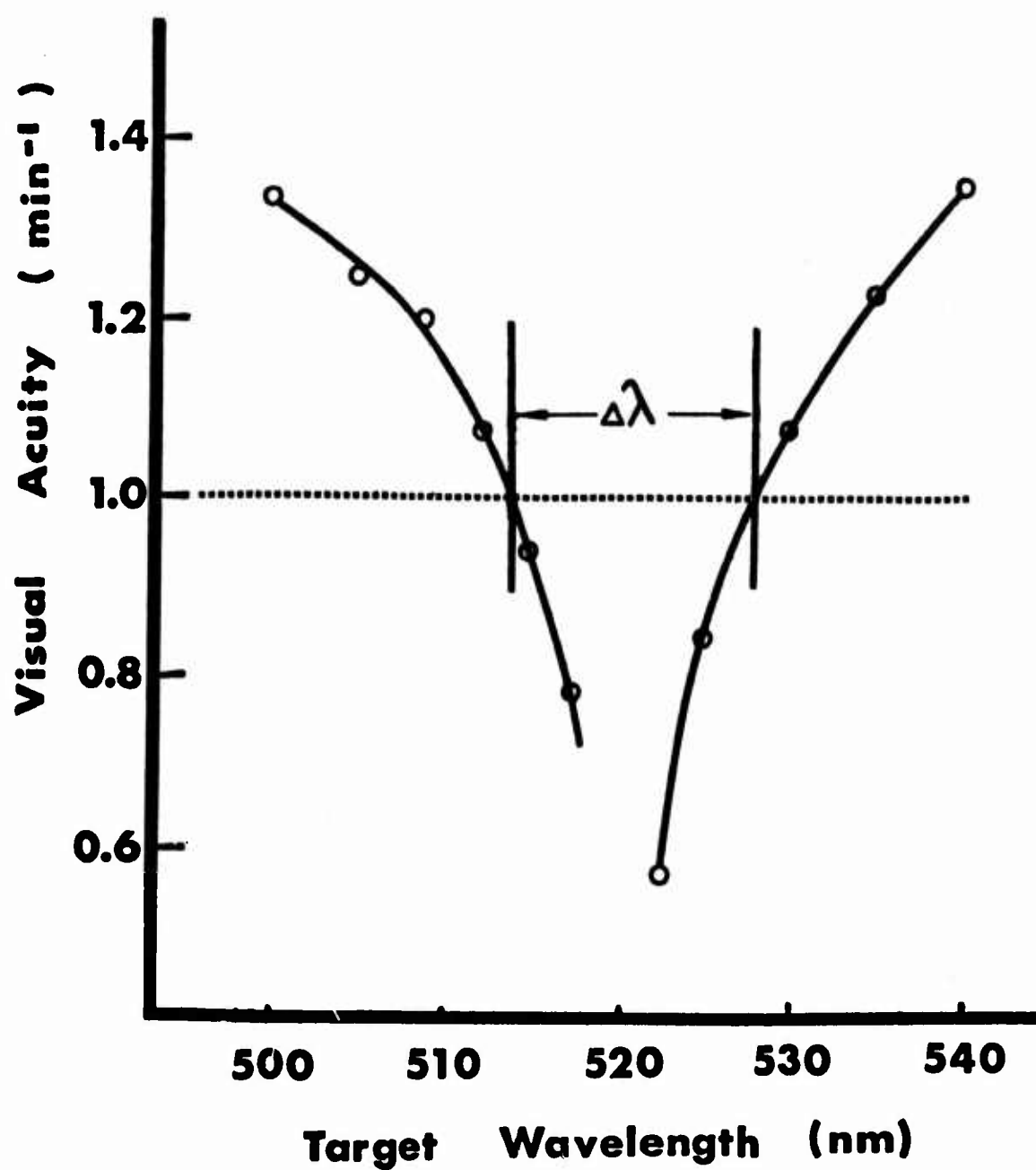for chromatic aberration.

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Fig. 11. Visual acuity measured with a grating in which one set of bars remained at 520 nm while the other set was varied above and below 520 nm in order to obtain acuity values which bracket 1.0.

Two other reasons also entered into the choice of this criterion: if the wavelength separation is sufficient, the individual bars can be resolved and their color can generally (although not always) be named. This is important because it indicates that at this visual angle acuity is in fact being mediated by the color mechanisms of the eye, and not by intensity gradients resulting from interference between two diffraction patterns or from an improper brightness match.

Secondly, the choice of a very gross criterion would transform this into a wavelength discrimination problem. It will be shown later that chromatic acuity and wavelength discrimination may be different phenomena.

The total wavelength interval ($\Delta \lambda$) is plotted against the wavelength of the fixed ("background") bars in Figure 12. This interval increases at long wavelengths.

Effect of Introducing Brightness Contrast

If we consider the amount of information delivered to the observer, it can be assumed that the test stimuli used here give virtually no information in the brightness dimension. It might be argued that deliberately disturbing the brightness match should improve acuity, since more information will be included in the stimulus. A test of this hypothesis shows that it only holds when the wavelength separation between adjacent bars is small (Figure 13). A slight brightness mismatch (0.1 log unit) improves acuity significantly in the region where both target and background are nearly the same wavelength (which incidentally indicates that the brightness matches were valid). A gross brightness mismatch (completely blocking one path) improves acuity over a wider interval around the equal wavelength point, but may actually degrade acuity when widely separated wavelengths are used. A general rule based on this and similar observations is that wavelength separation between target and background is a sufficient stimulus for good acuity. Once maximum acuity has been reached through wavelength separation, adding a brightness difference does not cause a further improvement in acuity.

Subjective Appearance of Fine Gratings

When target and background are nearly the same wavelength, visual acuity is poor. The grating can only be detected when the bars are quite wide. When the grating can be seen the hues of individual bars can also be identified. When target and background are widely separated in wavelength, however, the presence and orientation of the acuity target may be obvious at a much smaller visual angle than that at

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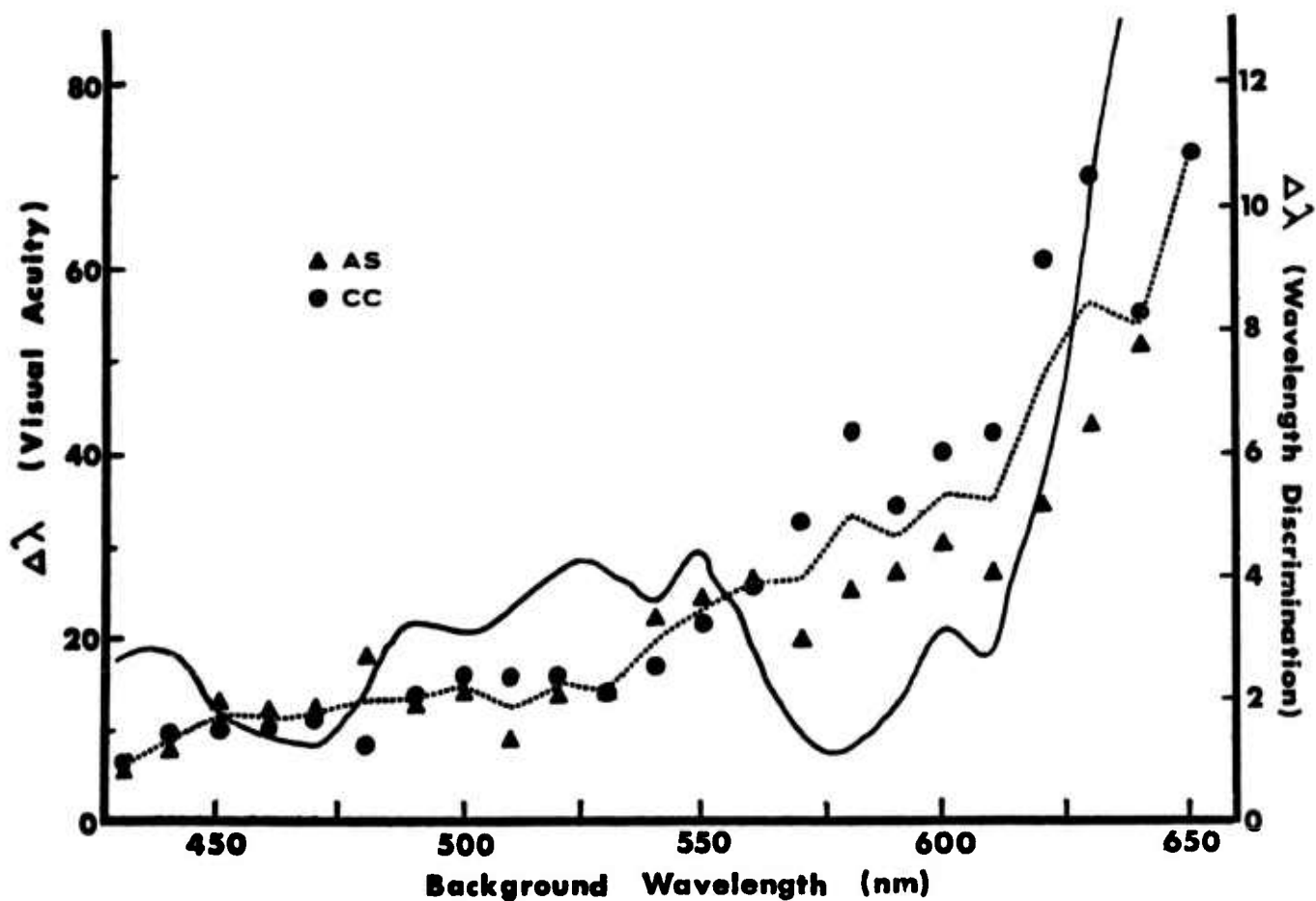
Fig. 12.　Comparison of chromatic visual acuity data and wavelength discrimination data. Points: Wavelength separation between target and background required to obtain visual acuity of 1.00 ($\Delta\lambda$ in Fig. 11). Dotted line: Mean of visual acuity data for two observers. Solid line: Wavelength separation required for wavelength discrimination. (Siegal, 1964.)

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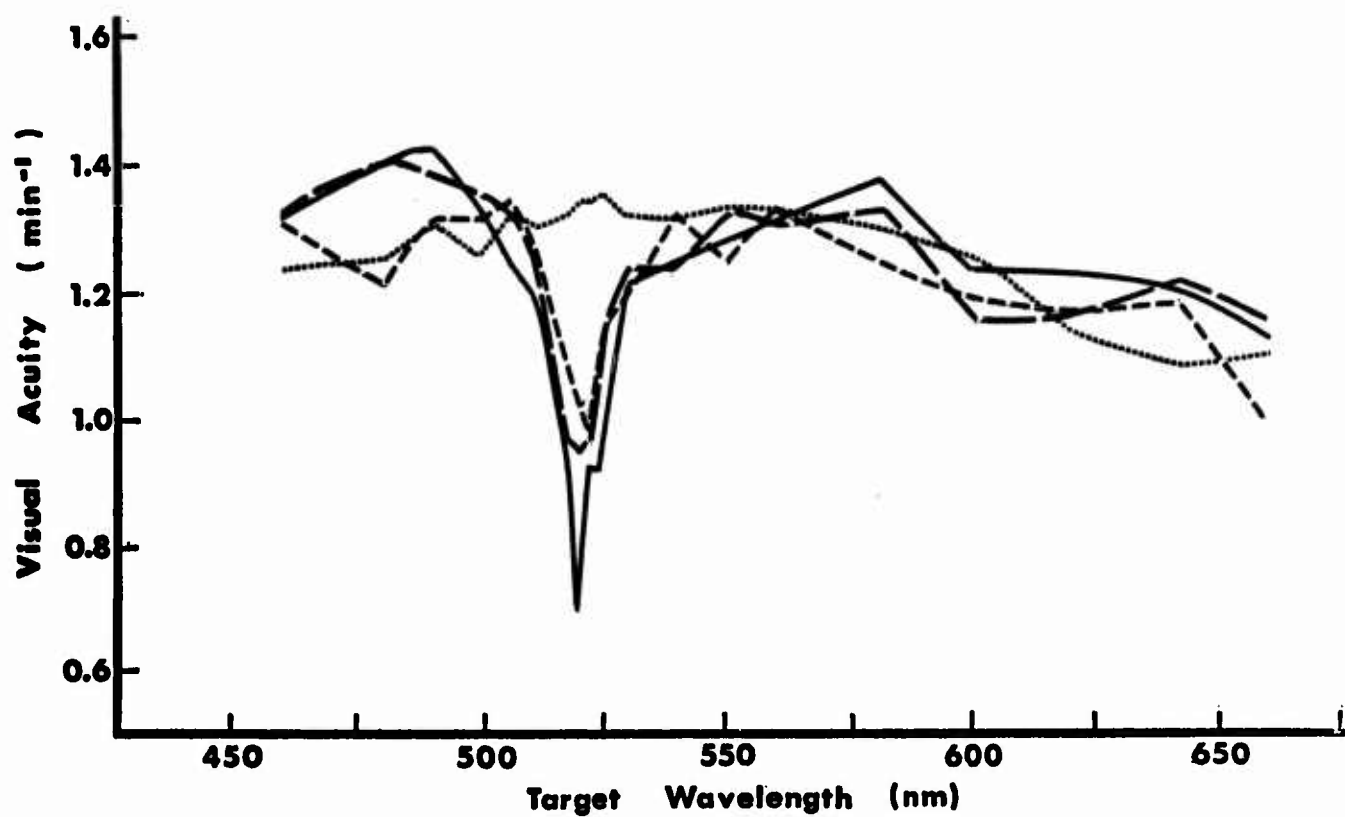
Fig. 13.   Effect of brightness mismatch. Solid line:
Visual acuity measured with target and back-
ground equated in brightness. Long dashes:
Background 0.1 log brighter than target at
all wavelengths. Short dashes: Target 0.1
brighter than background. Dotted line: Back-
ground dark. (Background remained at 520 nm
at all times, wavelength of target was varied.)

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which its hues can be identified. Under these conditions, the target appears as an achromatic pattern in a field which is a mixture of the target and background colors. This effect is particularly striking when target and background are complementary wavelengths, in which case the pattern appears as an achromatic pattern until the individual bars are made quite wide (more than 1 minute of arc). As the bars are made wider they rather suddenly appear to have hue.

The practical implication of this is that although chromatic stimuli may be used to enhance acuity in the absence of brightness contrast, the observer cannot be expected to identify the hues of the stimuli. In other words, don't color code small details.

The fact that patterns can be detected before their hue can be identified has also been observed by Bishop (1961) and in the Eastman Kodak report (1944).

Effect of Complementary Hues

There is no evidence in the present study that would suggest that better visual acuity can be attained by using complementary hues for the target and background. This agrees with Exner's earlier results for unsaturated stimuli (Exner, 1898) and extends his findings into the region of spectral colors.

IV. Discussion

It is not surprising that good visual acuity can be obtained with a grating which consists of alternating black and colored bars. Byram (1944) successfully resolved a monochromatic diffraction pattern in which the lines were separated by the equivalent of 0.35 minutes of visual angle, which is approximately half as large as the finest grating which could be resolved in the present study. Byram's stimulus produced an intensity gradient between adjacent retinal receptors, and his results can be explained by Hartridge's theory.

The unusual results of the present study are (1) the fact that good visual acuity can be maintained even when target and surround are equated in brightness and (2) the way in which acuity depends upon wavelength separation in different parts of the visible spectrum.

Concerning the first finding it should be noted that it is probably physically impossible to completely eliminate all brightness gradients on the retina while stimulating with two wavelengths. Due to diffraction, each bar of a grating is imaged on the retina not as a single bright band, but as a central bright band and a series of light and

dark bands. The distance between the center and any given light band is proportional to the wavelength of illumination. If alternating bars of the grating are of different wavelength, an interference pattern will be produced, with resulting intensity gradients. We do not believe that the present results are due to such an interference pattern, however, since the difference between the wavelength separations required to give an acuity of 1.00 at long and at short wavelengths is greater than would be predicted on the basis of interference patterns. Further, these interference produced gradients must be small compared to the large brightness contrast between adjacent bars when one set of bars is oc- cluded. If acuity depended on these gradients it should improve with greater contrast. This does not occur, however, as shown in the Results section. (Fig. 13.)

It is difficult to explain these results by means of any theory which requires a brightness contrast for good acuity, or which attri- butes acuity to a luminosity mechanism. Such a mechanism (either a separate receptor or a pooling of information from the color receptors) would be unable to discriminate between adjacent grating bars which were of equal brightness.

The second curious result of this study is shown by Figures 6 - 9 and Figure 12. We were initially skeptical that such a slight wavelength separation is needed between target and background in or- der to obtain good acuity in the blue region, but we have not been able to identify any experimental artifact which would produce this result.

We had predicted that the wavelength separation which is re- quired for good acuity would be directly related to wavelength discrim- ination, since if the wavelengths of target and background were made nearly the same and the individual bars were made very wide, we would in fact have a wavelength discrimination situation. The point at which chromatic acuity becomes wavelength discrimination cannot be established with the present data. The fact that they are different seems apparent, however, when we compare the wavelength separation necessary for a criterion acuity of 1.00 with the wavelength separa- tion required for hue discrimination. The two functions are shown in Figure 12. The vertical axis of the wavelength discrimination function has been arbitrarily adjusted so that it covers approximately the same range as the acuity functions. Even so, it bears little resemblance to the acuity functions. We have used Siegal's (1964) wavelength discrim- ination function since it is probably the most accurate data available. However, the classic data of Wright and Pitt (Wright, 1964, p. 169) come no closer to matching our data.

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The lack of agreement between chromatic acuity and wavelength discrimination is particularly surprising since MacAdam (1949) concluded on the basis of the Eastman Kodak (1944) data that the two are closely related. It may be that this only holds true for the unsaturated stimuli which were used in that study.

Possible Explanations for the Shape of the Wavelength Separation Function

In order to discriminate hue a minimum of two receptor types, which have different spectral sensitivity functions, must be stimulated. When both target and background are illuminated with energy from the long wavelength region of the spectrum, a large difference in wavelength is required between target and background before good acuity is attained. This probably indicates that only one receptor type is active in this region. This interpretation is supported by color matching and wavelength discrimination data, and by the limited published data which describe the absorption spectra of single cones. Toward the middle of the visible spectrum two or more receptor types are stimulated, and the wavelength separation between target and ground can be decreased while maintaining good acuity. This is predictable from the absorption spectra of the human visual pigments (Marks, Dobelle and MacNichol, 1964; Brown and Wald, 1964). It might be expected that at short wavelengths the wavelength separation required for good acuity should increase, since like in the long wavelength region, only one pigment is maximally sensitive. However, as shown above, there is no sign of acuity becoming worse at wavelengths as short as 430 nm, which was the limit of the present equipment.

The fallacy in the above argument may lay in not considering such factors as the relative luminance sensitivities of the receptor types, their distribution in the fovea and the absorption of the ocular media and macular pigmentation. For this reason, measurements of the spectral sensitivities of the color receptors performed with the intact eye, made by means of a psychophysical test (Wald, 1964) are probably more relevant to this problem. This study shows that the green pigment has a relatively high sensitivity to blue stimuli, so that the necessary qualification for hue discrimination (more than one functional receptor type) may be satisfied at short wavelengths. The receptors do not need to have a high absolute sensitivity in this region, since high intensity blue stimuli were used in order to permit brightness matching with the center of the spectrum. However, any explanation of this type runs into difficulty because it has to predict good wavelength discrimination in the short wavelength region, if equal luminance stimuli are used. Siegal (1964)

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and others have shown by experiment that this is not the case, while our data show that good chromatic acuity is maintained at wavelengths below that at which wavelength discrimination deteriorates.

We are unable at present to resolve this paradox, but believe that further investigation of the nature of chromatic acuity in the region below 430 nm may help identify the process which mediates it.

Military Significance of This Study

This study shows that good visual acuity can be maintained in the absence of brightness contrast, provided that an adequate wavelength difference exists between the objects to be discriminated. This may be of value in situations in which it is desirable to maintain a fixed adaptation level so that critical bright stimuli can be immediately detected. It should be noted, however, that when colored objects subtend a very small visual angle their hue cannot be identified, although their location or orientation may be clear to the observer. This point should be remembered when considering the use of colored materials in situations which require fine resolution, as in photointerpretation.

The wavelength separation which must be maintained between the acuity target and background increases in the long wavelength (red) region of the visible spectrum. Therefore, combinations of reds should be avoided if fine detail is to be discriminated. This has obvious implications in situations in which red illumination is used to maintain scotopic dark adaptation, as in aircraft instrument and cockpit lighting.

Further Research

The following areas should be investigated in order to better understand the phenomenon of chromatic acuity:

. Acuity should be studied in the region below 430 nm. The present study was limited by the use of a tungsten source, but this could be replaced by a xenon arc. The region below 430 nm is of interest since it is here that the greatest discrepancy occurs between chromatic acuity and wavelength discrimination data.

. A mathematical or graphical analysis should be made of the nature of the interference patterns which are created on the retina when adjacent stimuli differ in wavelength, with the goal of determining the maximum intensity contrast that could be caused by these patterns.

. The effect of varying stimulus purity should be investigated, in order to test the generality of these results. Most common objects have rather low saturation compared with the stimuli used in this study.

. Other stimulus patterns should be employed, in order to see whether these results are general or a function of the specific acuity measure used here.

References

Arnulf, A. & Flamant, F. Limites de resolution de l'oeil en lumiere monochromatique et applications a la vision instrumentale. Compt. Rend. Soc. Biol. 1950, 230, 1791-1793.

Baker, Katherine E. Some variables influencing vernier acuity. J. opt. Soc. Amer. 1949, 39, 567-576.

Bishop, H. P. Factors in acuity with chromatic test objects. Medford, Mass.: Tufts University, Institute for Psychological Research, December 1961.

Boltunow, A. Über die Sehscharfe im farbigen Licht. Zeit. f. Psychol. u. Physiol. d. Sinnesorg. 1908, 42, 359-372.

Brindley, G. S. The summation areas of human colour-receptive mechanisms at increment threshold. J. Physiol. 1954, 124, 400-408.

Brown, P. K. & Wald, G. Visual pigments in single rods and cones of the human retina. Science. 1964, 144, 45-52.

Brücke, E. Ueber einige Consequenzen der Young-Helmholtz'schen Theorie. I Abhandlung. Sitzungsber. d. Akad. d. Wiss., Wien. Kl. III. 80, 18-73 (1879); 84, 425. (n.v.). Cited in Liebmann (1927) and Exner (1898).

Byram, G. W. The physical and photochemical basis of visual resolving power, Part II. Visual acuity and the photochemistry of the retina. J. opt. Soc. Amer. 1944, 34, 718-738.

Cobb, P. W. The influence of illumination of the eye on visual acuity. Amer. J. Physiol. 1912, 29, 76-99.

Crook, M. N., Hanson, J. A., Shor, R. E., & Winterberg, R. P. The discrimination of simulated colored radar scope targets. Medford, Mass.: Tufts University, Institute for Applied Experimental Psychology, November 1959.

Eastman Kodak Co., Rochester, N. Y., Influence of color contrast on visual acuity. Cambridge, Mass.: National Defense Research Committee, November 1944. (Contract No. OEMsr-1070, OSRD No. 4541, ATI-23652.)

Exner, S. Studien auf dem Grenzgebiete des localisirten Sehens. Pfluger's Arch. ges. Physiol. 1898, 73, 117-171.

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Ferree, C. E., & Rand, Gertrude. Visibility of objects as affected by color and composition of light, Part I. With lights of equal luminosity or brightness. Person. J. 1931, 9, 475-492. Part II. With lights equalized in both brightness and saturation. Person. J. 1931, 10, 108-124.

Giese, W. J. The interrelationship of visual acuity at different distances. J. appl. Physiol. 1946, 30, 91-106.

Guilford, J. P. Psychometric methods. New York. McGraw-Hill. 1950.

Hartridge, H. Chromatic aberration and resolving power of the eye. J. Physiol. 1918, 52, 175-246.

Hartridge, H. The visual perception of fine detail. Phil. Trans. Roy. Soc. Lond. Series B., 1947, 232, 519-671.

Hartridge, H. Visual acuity and the resolving power of the eye. J. Physiol. 1922, 57, 52-67.

Hartinger, H. & Schubert, F. Ueber die Aenderung des Sehvermogens durch farbige Schutzglaser. Klin. monatsbl. f. Augen. 1940, 105, 337-356.

Hecht, S. The relation between visual acuity and illumination. J. gen. Physiol. 1928, 11, 255-281.

Hecht, S. & Mintz, Esther U. The visibility of single lines at various illuminations and the retinal basis of visual resolution. J. gen. Physiol. 1938, 22, 593-612.

Hecht, S., Peskin, J. C. & Patt, Marjorie. The relation between $\Delta I/I$ and intensity for different parts of the spectrum. J. gen. Physiol. 1938, 22, 7-19.

Hendley, C. D. The relation between visual acuity and brightness discrimination. J. gen. Physiol. 1948, 31, 433-457.

LeGrand, Y. Light, Colour and Vision. London: Chapman & Hall, 1957.

Liebmann, Susanne. Uber das Verhalten farbiger Formen bei Helligkeitsgleichheit von Figur und Grund. Psychol. Forsch. 1927, 9, 300-353.

Lythgoe, R. J. The measurement of visual acuity. Med. Res. Counc. Special Report Series No. 173. London: H. M. Stationery Office, 1932.

MacAdam, D. L. Colour discrimination and the influence of colour contrast on acuity. Doc. Ophthal. 1949, 3, 214-233.

Marks, W. B., Dobelle, W. H., & MacNichol, E. F. Jr., Visual pigments of single primate cones. Science, 1964, 143, 1181-1183.

Rice, D. E. Visual acuity with lights of different colors and intensities. New York: The Science Press. Arch. Psychol., 1912, No. 20.

Riggs, L. A. Visual acuity. Chapter 11 in C. Graham (Ed.), Vision and Visual Perception. New York: John Wiley, 1965.

Roaf, H. E. Visual acuity in light of different colours. Proc. Roy. Soc. (London), 1930, 106-B, 276-292.

Shlaer, S. The relation between visual acuity and illumination. J. gen. Physiol. 1937, 21, 165-188.

Shlaer, S., Smith, E. L., & Chase, A. M. Visual acuity and illumination in different spectral regions. J. gen. Physiol. 1942, 25, 553-569.

Siegal, M. H. Discrimination of color. IV. Sensitivity as a function of spectral wavelength, 410 through 500 mμ. J. opt. Soc. Amer. 1964, 54, 821-823.

Sumner, F. C. Influence of color on legibility of copy. J. app. Psychol. 1932, 16, 201-204.

von Lempicka, Wanda. Raumliche Farbenmischung auf der Netzhaut. Zeit. f. Psychol. u. Physiol. d. Sinnesorg. 1919, 50, 217-251.

Wald, G. Human vision and the spectrum. Science, 1945, 101, 653-658.

Westheimer, G. Visual acuity. In Annual Review of Psychology, Palo Alto: Annual Reviews, Inc. 1965.

Wright, W. D. The Measurement of Colour, Princeton, N. J.: Van Nostrand, 1964.

APPENDIX A

Method for Making Acuity Targets

The targets used in this study were gratings in which alternate bars were illuminated by two different sources of light. These targets were produced by a technique suggested by Dr. R. H. Peckham of the Eye Research Foundation. This method will be described in detail, since we believe that it is original and can be used to make any target which can be photographically reproduced in solid tones. The finished target is a mirror surface on a clear glass backing. This sort of target permits the use of two optical paths, one of which is reflected from the mirrored surface and the other transmitted by the clear areas of the target. The experimenter may then vary the intensity, wavelength, saturation, etc., of the stimulus and the background independently. Since the mirror coating is microscopically thin, virtually no boundary exists between stimulus and background.

The targets are made by etching clear areas out of the aluminum coating of a front surface mirror. Mirrors used were Edmund No. 40040. These were selected because of ready availability and reasonable price. Uniformity of the mirror coatings appears to be good except for numerous small scratches. If extremely accurate stimulus-background separation is required, it would probably be best to obtain better quality evaporated metal first surface mirrors.

The following steps were found adequate to produce mirror gratings with 300 line pairs per inch:

1. Flood the mirror with acetone, then rinse in running water. If the surface is clean, the water should run off without leaving spots.

2. Pour on Kodak OrthoResist (KOR), diluted with its own volume of KOR thinner. Tilt mirror back and forth until coated, then pour off excess and stand on edge to dry. Dry about 10 minutes at 170° F. When dry, the surface is light sensitive and must be handled in yellow or red safelight.

3. Place desired pattern over the sensitized mirror and expose to light. Two minutes exposure at 2 feet from a 125 watt mercury lamp, or about 30 seconds in sunlight worked well with the coatings we used. If it is necessary to enlarge or to reduce the stimulus

pattern, it can be projected on the sensitized mirror with a slide projector. As a rule of thumb, KOR is about as sensitive as contact paper. Heavy coatings require longer exposure.

4. Develop 2 minutes in KOR developer. Flush with xylene (poured on or squirted with an ear syringe).

5. Wash with tap water. A properly exposed surface can be washed in the direct stream from a faucet. When clean, the surface should shed water and have a uniform appearance (no drops of water or obvious discontinuities other than the desired pattern).

6. Bake for about 10 minutes at 170° F. This hardens the remaining KOR surface and removes any remaining developer.

7. (Applicable only if using first surface mirrors with a silicon dioxide coating):

a. Etch for 1 minute in 0.5% hydrofluoric acid. DO NOT AGITATE! Watch the surface carefully. At the first sign of loosening of the KOR coating, remove the preparation and wash thoroughly.

Complete the etch in 20% KOH, If the HFl etch was properly done, the areas exposed to light are still protected by a covering of SiO_2. Consequently, the KOH will not attack them. However, the KOH etch will creep under the SiO_2 coating if given time; therefore, etch for only a few seconds, then wash and examine under a microscope. Repeat if necessary. Etch only long enough to get a clear glass background. If the unexposed areas are white (rather than silver) in the final grating, it probably means that they were reached by HFl. A shiny but pitted surface results from too long an etch in KOH.

b. (Applicable if using chemically deposited silver mirrors): If fine detail is not required, it is possible to use ordinary back surface mirrors. These mirrors have a chemically deposited silver surface protected by a layer of copper. With these mirrors, the KOR coating is applied to the back of the mirror and the entire etch done with dilute HNO_3.

Due to the uneven thickness of the silver-copper layer, it is impossible to obtain a clean glass-mirror boundary with back surface mirrors.

8. Unwanted KOR can be removed from the finished target with acetone, methyl ethyl ketone, or KOR developer.

Proper KOR exposure is easy to identify with a little practice. An over-exposed KOR coating has a crinkled or alligator hide appearance when viewed under magnification. Under-exposure results in

exposed areas washing away with the unexposed areas during development. (The effect of light on KOR is to render it insoluble in KOR developer.) Correct exposure varies with coating thickness, heavy coatings requiring a longer exposure.

KOR is not sensitive to light until dry; therefore, the initial coating of the mirror may be carried out in room light. Subsequent steps (through development) must be done under yellow safelight. Etch may be done in room light.

Unlike photographic emulsions, KOR appears to have no grain. Thus, the sharpness of the final target seems to depend on the evenness of the mirror coating and the care with which the KOR is exposed and developed.

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13. ABSTRACT

Previous studies of visual acuity have dealt almost exclusively with achromatic brightness differences. The present study measures acuity under conditions in which the target and surround are equated in brightness but differ in wavelength. It has been suggested that acuity should always be less under these conditions, since monochromatic stimuli may stimulate fewer foveal color sensitive receptors than "white" stimuli. Light from two monochromators illuminated alternate bars of a grating target. The resulting stimuli were presented in modified Maxwellian view and appeared to the observer as a 1° grating of colored lines in a neutral surround. A zoom system varied the angular subtense of the lines. When the grating consisted of alternate colored and black lines acuity was fairly constant (about 1.30) from 430 nm to 670 nm. Equally good acuity could be obtained when alternate lines were matched for brightness, provided that the wavelength separation between adjacent lines was adequate. This separation is minimum in the blue and increases toward the red; it does not appear to be simply related to wavelength discrimination. When maximum acuity has been reached by wavelength separation no further improvement can be made by introducing a brightness difference. It is concluded that wavelength difference can be a sufficient condition for good visual acuity. (U)

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